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Vision 2023: Assessing the feasibility of electricity and biogas production from municipal solid waste in Turkey

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ABSTRACT

Turkey imports most of its energy. However, according to the recently avowed Vision 2023 agenda the country also plans to produce 30% of its electricity demand from renewable energy sources by 2023. Meanwhile, each year around 25 million tonnes of municipal solid waste (MSW) is generated nationwide. Not only MSW pollutes the environment handling, processing and storage requires precious labour and capital. In that context, a synergistic solution can be created between MSW management and energy supply. In this study, economics and environmental impacts of electricity generation from MSW via (i) direct combustion and (ii) biogas harnessing in 81 cities of Turkey is analysed in detail for a period between 2012 and 2023. Firstly, it is estimated that nationwide 8500 GWh of electricity could have been generated by direct combustion of MSW in 2012. This is predicted to rise 9700 GWh in 2023. It is calculated that 3100 million m^3 of methane would be emitted from the landfills of Turkey in 2012. If no action taken this would rise to 3600 million m^3 in 2023. Furthermore, it is estimated that by capturing 25% of this methane via landfill bioreactors 2900 GWh or 0.5% of Turkey's annual electricity demand could be supplied in 2023. Simulations also showed that by realizing apposite landfill investments by 2023 annual energy savings worth 200–900 million € could be generated from MSW. Consequently, this could lead to greenhouse gas emission savings up to 11.0 million tonnes of CO_2 per annum.

Contents

1. Introduction

In 1950s, Turkey was a developing country with a population slightly over 20 million people [1]. As the country's economy is mostly based on agriculture, nearly 75% of this population was living in villages, and only the remaining 25% reside in cities and towns [2]. However, in the last 60 years, Turkey transformed from an agricultural nation to an industrialised one. Today, the country is a member of G20 industrialised nations with a gross domestic product (GDP) around 1 trillion US$ and considered as a major regional power [3–5]. Throughout this half-century alteration

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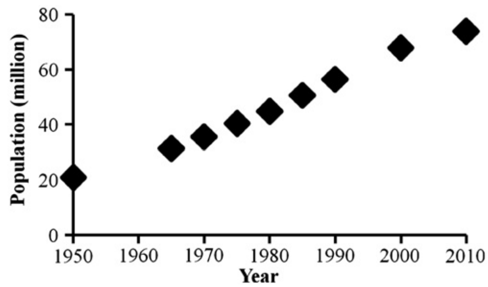

Fig. 1. Population change of Turkey between 1950 and 2010.

majority of the population moved from villages to cities. At the end of the year 2011, Turkey's population was around 75 million people, and 76% of this population were living in cities, while only the remaining 24% in villages [6]. The population change of Turkey between 1950 and 2011 is shown in Fig. 1 [1,6].

As the country transforms, people living in 81 cities of Turkey need colossal amounts of energy & goods, and consequently generate vast amounts of municipal solid waste (MSW). However, Turkey has limited indigenous energy resources and imports around 65% of its primary energy [7]. The country's energy bill in the year 2011 was $54 billion and according to finance minister, Mr. Mehmet Simsek, this bill could rise up to staggering $65 billion by the end of 2012 [8]. According to the central bank data, Turkey's 2011 current account deficit was $77.8 billion, and more than 50% of this deficit was due to the dependence on foreign energy sources; petroleum and natural gas [9–11]. As a result, energy supply to the cities of Turkey is becoming more expensive each day, and creates a major burden on the country's economic growth and sustainability goals.

In addition to the thirst for energy, due to the fast growing consumption trends powered by a growing affluence of the working class, the cities of Turkey generate massive amounts of municipal solid waste. According to the Turkish Statistical Institute, countrywide around 25 million tonnes of municipal solid waste was generated in the year 2010 [12]. Rapid population growth, blending with the intensity of municipal solid waste generation and hot climatic conditions result in increasing environmental problems [13]. In Turkey, only a tiny fraction of municipal solid waste is recycled and more than 97% ends in landfill sites.

Landfills are considered as a primary waste management option in Turkish cities; however, they cause major environmental problems [14]. Anthropogenic methane and carbon dioxide emissions due to anaerobic digestion of organic components, water pollution due to leachate production, unpleasant odours, asphyxiation, and vegetation damage are the most common type of problems associated with landfills [15,16]. According to the European Union (EU) landfill directive (1999/31/EC) the amount of biodegradable organic waste deposited in landfills should be decreased by 65% of the 1995 level by 2016 [17]. As an associate member to the European Union, Turkey will eventually have to fulfill this target, which currently lacks far behind. Therefore, urgent innovative solutions must be found to tackle the municipal solid waste problem of Turkish cities and luckily one may lie in the waste management system.

Municipal solid waste can be treated as a resource due to its moderate energy content and high organic fraction, and within the framework of alleged integrated waste management systems could be used for power generation [18]. As a primary option, in dedicated waste to energy plants located at landfills MSW can be combusted in mass burners to produce electricity. Burning waste at extremely high temperatures destroys chemical compounds and disease causing bacteria [19]. However, incineration produces carbon dioxide, nitrogen oxides and sulphur dioxide as well as trace amounts of toxic pollutants, such as mercury compounds and dioxins [20,21]. Alternatively, biogas, a renewable energy source containing methane and carbon dioxide that has already been produced by anaerobic digestion of MSW at the landfills, can be harnessed for power generation. Since both methane and carbon dioxide are greenhouse gasses, their collection could also help to tackle global warming and climate change.

The government of Turkey plans to produce 30% of the country's electricity demand at the year 2023 from renewable energy sources to uphold a sustainable economic growth, tackle climate change, and fulfill European Union targets [22,23]. However, due to limited renewable energy investments so far, constant expansion of population and growing industrial activities makes the feasibility of such an ambitious goal speculative. In that context, a synergistic solution can be created between municipal solid waste management and energy supply for Turkish cities. In this paper: Feasibility, potential, economic, and environmental impacts of electricity generation via combustion and biogas recovery from municipal solid waste in 81 cities of Turkey is analysed in detail, for a time span between 2012 and 2023. Detailed review of the literature showed that there is not any detailed work related to the estimation of this potential so far.

2. Theory/calculations

2.1. Population growth, municipal solid waste generation and electricity consumption in 81 cities of Turkey, between 2012 and 2023

In order to calculate the electricity and methane production potentials from the landfills in 81 cities of Turkey: (i) Population and municipal solid waste generation, between the years 2012 and 2023, (ii) composition and calorific value of municipal solid waste must be calculated precisely. Together with this data (iii) electricity consumption projections, in the same period, must be calculated for the technical feasibility analysis of electricity production from MSW at landfills. This section is designated for the calculation and estimation of such data.

2.1.1. Population growth in 81 cities of Turkey, between 2012 and 2023

Since 1950s, there has been almost a constant increase in Turkey's population. Both municipal solid waste generation and electricity consumption is directly related to population growth. Therefore, its precise estimation is utmost importance. The most common methods used in the literature for the estimation of population growth are Malthusian growth theory and logistic equations [24,25]. The population change in Turkey is monitored by the government agency, Turkish Statistical Institute (TurkStat), which uses a Malthusian based approach in their population growth projections. Correspondingly, a modified Malthusian model developed unique to this study, as shown in Eq. (1), is used to predict the population of Turkish cities, between 2012 and 2023.

$$P_t = P_{t-1} e^{k_p t} \tag{1}$$

in Eq. (1), t is time of interest in years, P_t is the estimated population at year t, P_{t-1} is the population at the previous year of concern, and k_p is annual population growth rate constant. In this study, k_p values reported in Table 1 are taken from the Turkish Statistical Institute, which were estimated and projected based on data from Address Based Population Registration System (ABPRS) in 2008 and have been revised according to the final result of 2008 Turkey Demographic and Health Survey [26]. Using the statistical functions provided by the software SigmaPlot 11

Table 1
Annual population growth rate for Turkey, between 2011 and 2023 [26].

Year	Annual population growth rate, %
2011	0.128
2012	0.125
2013	0.118
2014	0.117
2015	0.114
2016	0.111
2017	0.108
2018	0.102
2019	0.099
2020	0.097
2021	0.094
2022	0.091
2023	0.083

Table 2
Estimated population for 81 cities of Turkey, between 2012 and 2023, based on Eq. 1.

City	Year		
	2012	2018	2023
Adana	2,138,654	2,286,853	2,395,464
Adıyaman	606,076	648,075	678,854
Afyonkarahisar	715,432	765,009	801,341
Ağrı	555,910	594,432	622,664
Amasya	343,364	367,158	384,595
Ankara	4,893,981	5,233,111	5,481,649
Antalya	2,029,023	2,169,625	2,272,668
Artvin	168,981	180,690	189,272
Aydın	1,015,225	1,085,575	1,137,133
Balıkesir	1,181,849	1,263,745	1,323,765
Bilecik	231,156	247,174	258,913
Bingöl	261,708	279,843	293,134
Bitlis	337,191	360,557	377,681
Bolu	278,157	297,432	311,558
Burdur	265,501	283,899	297,382
Bursa	2,672,255	2,857,430	2,993,139
Çanakkale	502,962	537,815	563,358
Çankırı	183,655	196,382	205,708
Çorum	549,124	587,175	615,062
Denizli	955,699	1,021,924	1,070,459
Diyarbakır	1,568,134	1,676,799	1,756,435
Edirne	400,432	428,180	448,516
Elazığ	566,806	606,083	634,868
Erzincan	230,713	246,700	258,417
Erzurum	788,791	843,451	883,509
Eskişehir	784,175	838,515	878,338
Gaziantep	1,744,341	1,865,216	1,953,802
Giresun	429,998	459,795	481,633
Gümüşhane	132,939	142,151	148,902
Hakkari	257,741	275,601	288,691
Hatay	1,518,507	1,623,733	1,700,849
Isparta	459,785	491,646	514,996
Mersin	1,690,123	1,807,241	1,893,072
İstanbul	13,595,332	14,537,427	15,227,858
İzmir	4,050,028	4,330,677	4,536,355
Kars	309,498	330,945	346,663
Kastamonu	370,478	396,150	414,964
Kayseri	1,266,286	1,354,034	1,418,342
Kırklareli	341,318	364,970	382,303
Kırşehir	227,561	243,330	254,887
Kocaeli	1,600,113	1,710,994	1,792,254
Konya	2,065,445	2,208,571	2,313,464
Kütahya	605,626	647,593	678,350
Malatya	759,620	812,259	850,835
Manisa	1,414,830	1,512,872	1,584,723
Kahramanmaraş	1,071,587	1,145,843	1,200,263
Mardin	763,685	816,605	855,388
Muğla	838,450	896,550	939,131
Muş	417,312	446,229	467,422
Nevşehir	289,571	309,637	324,343
Niğde	346,590	370,607	388,208
Ordu	737,610	788,724	826,183
Rize	327,827	350,544	367,192
Sakarya	895,237	957,273	1,002,737
Samsun	1,284,790	1,373,821	1,439,068
Siirt	308,400	329,770	345,432
Sinop	207,935	222,344	232,904
Sivas	658,680	704,323	737,774
Tekirdağ	818,559	875,281	916,851
Tokat	633,632	677,540	709,718
Trabzon	783,282	837,560	877,339
Tunceli	78,664	84,115	88,110
Şanlıurfa	1,705,991	1,824,209	1,910,846
Uşak	346,680	370,703	388,309
Van	1,061,948	1,135,536	1,189,467
Yozgat	488,295	522,132	546,929
Zonguldak	635,582	679,624	711,902
Aksaray	387,178	414,007	433,670
Bayburt	76,319	81,607	85,483
Karaman	238,594	255,127	267,244
Kırıkkale	283,735	303,397	317,806
Batman	523,273	559,533	586,107
Şırnak	441,130	471,698	494,100
Bartın	192,569	205,913	215,693
Ardahan	108,156	115,651	121,143
Iğdır	189,143	202,250	211,856
Yalova	208,961	223,441	234,053
Karabük	233,442	249,618	261,474
Kilis	126,290	135,041	141,455
Osmaniye	491,500	525,559	550,519
Düzce	346,853	370,889	388,503
Total	75,611,975	80,851,542	84,691,451

and Microsoft Excel 2007, the population projections between 2012 and 2023 are calculated and reported in Table 2.

It is estimated that Turkey's population will reach to 85 million in the year 2023. This prediction matches fairly with the one reported by the Turkish Statistical Institute as 84 million [27]. The cities: Istanbul, Ankara and Izmir, will inhabit 15.2, 5.5, and 4.5 million people, respectively, or 32% of the country's population in total by 2023. It is also predicted that more than 80% of the population will live in cities by 2023, which is currently at 76%.

2.1.2. Municipal solid waste generation in 81 cities of Turkey, between 2012 and 2023

Planning and design of municipal solid waste management systems need accurate solid waste generation predictions. However, achieving the desired prediction accuracy is quite challenging in fast growing regions as urbanisation and population growth directly contributes to municipal solid waste generation [28,29]. Traditional forecasting methods for municipal solid waste generation generally consider demographic and socioeconomic factors on per capita basis, which may either be taken as time independent or may be projected to change with time [28]. In the current study, a linear relationship with population growth is assumed. Consequently, municipal solid waste generation in 81 cities of Turkey is estimated using a modified exponential growth model, Malthusian based, as shown in Eq. 2, between 2012 and 2023.

$$MSW_t = MSW_{t-1}e^{k_m t} \tag{2}$$

In Eq. (2), t is time of interest in years, MSW_t is the estimated municipal solid waste in tonnes at year t, MSW_{t-1} is the municipal solid waste in tonnes at the previous year of concern, and k_m is the

annual municipal solid waste growth rate constant, which is assumed to be equal to k_p values reported in Table 1. Using the statistical functions provided by the software SigmaPlot 11 and Microsoft Excel 2007, the municipal solid waste generation projections, between 2012 and 2023 are calculated and reported in Table 3.

It is estimated that municipal solid waste generation in Turkey will reach to 29 million tonnes per annum, by the year 2023. Even with the current generation rate most of Turkish cities has major environmental problems related to municipal solid waste management. Therefore, by the year 2023, this problem will hang like the sword of Damocles on the country's environmental sustainability goals, if no action has taken place.

Table 3
Estimated municipal solid waste generation for 81 cities of Turkey, between 2012 and 2023, based on Eq. (2), tonnes.

City	Year		
	2012	2018	2023
Adana	847,003	905,697	948,711
Adıyaman	137,392	146,913	153,890
Afyonkarahisar	253,583	271,155	284,033
Ağrı	107,478	114,926	120,384
Amasya	126,503	135,270	141,694
Ankara	2,052,875	2,195,130	2,299,384
Antalya	918,617	982,274	1,028,925
Artvin	31,848	34,055	35,672
Aydın	352,100	376,499	394,381
Balıkesir	456,736	488,386	511,581
Bilecik	74,719	79,896	83,691
Bingöl	66,573	71,186	74,567
Bitlis	69,256	74,055	77,572
Bolu	94,177	100,703	105,486
Burdur	73,936	79,060	82,814
Bursa	879,623	940,577	985,248
Çanakkale	158,484	169,467	177,515
Çankırı	55,513	59,360	62,179
Çorum	161,876	173,093	181,314
Denizli	287,572	307,500	322,104
Diyarbakır	389,899	416,917	436,718
Edirne	199,049	212,842	222,951
Elazığ	203,264	217,349	227,672
Erzincan	85,594	91,526	95,873
Erzurum	193,323	206,719	216,537
Eskişehir	281,364	300,861	315,150
Gaziantep	423,821	453,190	474,714
Giresun	87,353	93,407	97,843
Gümüşhane	26,844	28,704	30,067
Hakkari	27,412	29,311	30,703
Hatay	386,800	413,604	433,247
Isparta	143,514	153,459	160,748
Mersin	579,556	619,716	649,149
İstanbul	5,877,847	6,285,155	6,583,658
İzmir	1,728,850	1,848,652	1,936,450
Kars	68,235	72,963	76,428
Kastamonu	116,888	124,988	130,924
Kayseri	474,589	507,476	531,578
Kırklareli	148,089	158,351	165,871
Kırşehir	89,594	95,803	100,353
Kocaeli	526,562	563,050	589,791
Konya	669,825	716,241	750,257
Kütahya	299,652	320,417	335,634
Malatya	213,722	228,532	239,386
Manisa	493,596	527,800	552,867
Kahramanmaraş	262,737	280,943	294,286
Mardin	151,019	161,484	169,153
Muğla	407,447	435,681	456,373
Muş	50,250	53,733	56,284
Nevşehir	109,530	117,120	122,683
Niğde	119,774	128,074	134,157
Ordu	154,918	165,653	173,521
Rize	60,425	64,612	67,680
Sakarya	245,765	262,795	275,276
Samsun	316,423	338,350	354,419
Siirt	68,711	73,472	76,961
Sinop	65,273	69,796	73,111
Sivas	187,633	200,635	210,163
Tekirdağ	385,948	412,692	432,293
Tokat	203,356	217,448	227,775
Trabzon	151,397	161,888	169,577
Tunceli	23,220	24,829	26,008
Şanlıurfa	318,918	341,018	357,214
Uşak	117,597	125,746	131,718
Van	206,995	221,339	231,851
Yozgat	125,481	134,176	140,549
Zonguldak	151,724	162,238	169,944
Aksaray	114,455	122,387	128,199
Bayburt	18,373	19,646	20,579
Karaman	64,453	68,920	72,193
Kırıkkale	136,132	145,565	152,479
Batman	115,690	123,707	129,582
Şırnak	121,983	130,436	136,631
Bartın	50,173	53,650	56,198
Ardahan	17,103	18,288	19,157
Iğdır	47,658	50,960	53,380
Yalova	71,603	76,565	80,201
Karabük	67,647	72,335	75,770
Kilis	35,529	37,991	39,795
Osmaniye	109,755	117,360	122,934
Düzce	128,145	137,025	143,533
Total	25,924,354	27,720,794	29,037,347

2.1.3. *Energy content of municipal solid waste in 81 cities of Turkey*

Globally, average energy content and composition of municipal solid waste is highly variable depending on the economy, cuisine, geographical location and removal of materials for recycling trends. In the literature, there are various estimates for the calorific values of municipal solid waste. However, as rule of thumb, higher water or moisture content results in lower calorific value. Azapagic and Perdan reported that the higher heating values of municipal solid waste can change between 10 and 30 MJ/kg around the world [30]. Therefore, depending on the moisture content, lower heating values or calorific values of municipal solid waste can change between 5 and 20 MJ/kg. Similarly, International Energy Agency (IEA) reported that a tonne of municipal solid waste should have a calorific value between 8 and 12 MJ/kg for power generation [31].

Generally, data for the calorific value and composition of municipal solid waste are collected by local disposal authorities. However, current literature analysis showed that there is a crucial lack of information for such data in the literature for majority of cities in Turkey except for Istanbul, Izmir, Denizli and Gumushane. In 2012, Yildiz et al. reported that, in Istanbul approximately 54% of the municipal solid waste composition was of organic in dry basis, and average moisture content and calorific value as 62.41% and approximately 6 MJ/kg [32]. Also, in 2005, Kanat has reported that around 54% of the municipal solid waste in Istanbul was organic content in dry basis, and moisture content around 70% [33]. In 2005, Dolgen et al. reported that the calorific value is between 3.5 and 5.5 MJ/kg and moisture content is between 50% and 57% for the municipal solid waste in Izmir [34]. In 2009, Agdag reported in 2009 that the municipal solid waste in Denizli had an organic content of 70% (dry basis), moisture content of 65% (dry basis) and an average calorific value of 5.2 MJ/kg [35]. In 2008, Nas and Bayram reported that the municipal solid waste in Gumushane had an organic content of 93%, moisture content of 77%, and an average calorific value of approximately 2.1 MJ/kg [36].

Table 4
Average calorific value, moisture and organic content of municipal solid waste in Turkey.

Parameter	Range
Calorific value (MJ/kg)	2.0–6.0
Moisture content (%)	65%–80%
Organic content (% dry basis)	50%–95%

According to Turkish Statistical Institute data gross domestic product at purchasing power parity per capita, GDP (PPP), of Gumushane is amongst the lowest in the country, Denizli is slightly above the country average, and Istanbul–Izmir are amongst the highest countrywide. Municipal solid waste generation is directly proportional to gross domestic product (GDP) growth and share of the organics can decrease with increasing GDP [37,38]. Therefore, it is assumed that average calorific value, moisture and organic content of MSW in 81 cities of Turkey could be in the ranges given in Table 4, depending on the local purchasing power based on GDP, cuisine and diet.

2.1.4. *Electricity consumption in 81 cities of Turkey, between 2012 and 2023*

It is generally accepted that electricity consumption plays a significant role in economic development, not only it enhances the productivity of capital, labour and other factors of production, but also increased consumption of electricity implies higher economic status of a country and many studies have shown that countries with high GDP per capita have shown to have high electricity consumption per capita [39]. There are various models for the estimation of electricity consumption. The most common methods that has been used to forecast medium to long term energy demand of Turkey are Autoregressive Integrated Moving Average (ARIMA), seasonal ARIMA (SARIMA) and MAED (Model for Analysis of Energy Demand) [40,41]. Others suggested that a simple exponential regression model, Holt Winters, can provide more sensible results for the electricity demand estimations in Turkey [42]. Similarly, in a recent study by the author of this paper electricity consumption for Turkey, between 2010 and 2023, is predicted via a simple exponential model and it is planned to continue in that direction [43]. As a leap forward, in the electricity consumption forecast population change also plays an important role and generally simple first order regression models can lack in grasp of that detail. Providentially, this can be augmented via using a demographics based approach. In this study, a second order exponential model as shown in Eq. (3) is developed to estimate electricity consumption in Turkish cities, between 2012 and 2023.

$$E = P_i e^{k_p t} E_0 e^{k_e t} \tag{3}$$

In Eq. (3), t is time in years; E_0 is electricity consumption per capita at the base year, kWh/capita; E is electricity consumption at year t in GWh; k_e is the electricity consumption growth rate, P_t is the estimated population in year t, P_i is the population at the reference year, and k_p is annual population growth rate constant. E_0 values are taken from Turkey Electricity Distribution Company (TEDAS) [44], t_0 as 2010, the constant k_e was previously calculated as 0.0765 by the author [43], k_p values were taken from Table 1. Using Eq. 3, electricity consumption in 81 cities of Turkey between 2012 and 2023 is estimated and reported in Table 5.

Using Eq. (3), Turkey's total electricity consumption at the year 2023 is estimated as 534,317 GWh. This prediction matches quite fairly with the reported data in literature: 500,000 GWh [45] and 560,000 GWh [46], and the one previously calculated by the author as 530,000 GWh [43]. Using the electricity consumption

Table 5
Estimated electricity consumption for 81 cities of Turkey, between 2012 and 2023 based, on Eq. (3), GWh.

City	Year		
	2012	2018	2023
Adana	4785	8097	12,433
Adıyaman	1076	1821	2796
Afyonkarahisar	1334	2258	3467
Ağrı	373	631	968
Amasya	557	943	1448
Ankara	11,433	19,346	29,708
Antalya	6244	10,565	16,223
Artvin	358	605	930
Aydın	1987	3362	5163
Balıkesir	2951	4994	7668
Bilecik	1395	2361	3625
Bingöl	168	284	437
Bitlis	260	440	675
Bolu	965	1632	2506
Burdur	905	1532	2352
Bursa	10,247	17,340	26,626
Çanakkale	4068	6884	10,571
Çankırı	300	508	780
Çorum	809	1369	2102
Denizli	2972	5029	7722
Diyarbakır	1450	2453	3767
Edirne	1197	2026	3111
Elazığ	1140	1929	2962
Erzincan	317	537	825
Erzurum	1109	1876	2881
Eskişehir	2331	3945	6057
Gaziantep	5046	8538	13,111
Giresun	539	912	1401
Gümüşhane	183	310	476
Hakkari	148	251	386
Hatay	6051	10,239	15,722
Isparta	1039	1758	2699
Mersin	3681	6229	9566
İstanbul	36,483	61,735	94,798
İzmir	17,811	30,139	46,281
Kars	318	539	828
Kastamonu	760	1287	1976
Kayseri	3380	5720	8783
Kırklareli	1881	3183	4888
Kırşehir	407	688	1057
Kocaeli	12,965	21,938	33,688
Konya	5708	9660	14,833
Kütahya	1393	2357	3620
Malatya	1344	2274	3492
Manisa	3480	5888	9042
Kahramanmaraş	3585	6067	9316
Mardin	1219	2063	3167
Muğla	2400	4061	6236
Muş	358	605	930
Nevşehir	662	1120	1720
Niğde	929	1571	2413
Ordu	1054	1784	2739
Rize	685	1159	1780
Sakarya	2350	3976	6105
Samsun	2281	3860	5927
Siirt	363	614	943
Sinop	321	543	834
Sivas	1341	2269	3484
Tekirdağ	6367	10,773	16,543
Tokat	752	1272	1954
Trabzon	1231	2083	3199
Tunceli	97	164	252
Şanlıurfa	2975	5034	7730
Uşak	1081	1830	2810
Van	867	1467	2253
Yozgat	607	1027	1578
Zonguldak	3046	5155	7915
Aksaray	661	1119	1718
Bayburt	83	141	216
Karaman	576	975	1497
Kırıkkale	628	1063	1632
Batman	559	946	1453

Table 5 (*continued*)

City	Year		
	2012	2018	2023
Şırnak	330	559	858
Bartın	337	570	875
Ardahan	98	166	255
Iğdır	128	217	334
Yalova	929	1572	2414
Karabük	926	1566	2405
Kilis	153	259	398
Osmaniye	1435	2429	3730
Düzce	867	1468	2254
Total	205,632	347,960	534,317

data the technical and economical feasibility of electricity generation from municipal solid waste either by combustion in mass burners or methane harnessing can be estimated in the cities of Turkey between 2012 and 2023.

3. Results and discussion

3.1. Electricity generation potential via combustion of municipal solid waste in 81 cities of Turkey, between 2012 and 2023

According to the World Bank technical guidance report for electricity generation from municipal solid waste via combustion in mass burners, the average lower calorific value of the municipal solid waste must be at least 6 MJ/kg throughout all seasons and the annual average lower calorific value must not be less than 7 MJ/kg and the annual amount of waste for combustion should not be less than 50,000 metric tonnes [47]. Therefore, due to high moisture content and lower calorific value of the municipal solid waste, see Table 4, direct energy recovery from municipal solid waste via combustion seems not to be a feasible option for majority of Turkish cities. Similar conclusions were also obtained by others [34]. Alternatively, recovery of energy through municipal solid waste combustion in Turkey could be carried out via utilisation of an auxiliary fuel such as natural gas or coal via co-firing technology. Due to large scale of coal or natural gas fired boilers for electricity production, co-firing of municipal solid waste could consume large quantities of waste [48], and therefore, could offer economic and environmental benefits.

As reported in Table 3, in the cities Artvin, Gumushane, Hakkari, Mus, Tunceli, Bayburt, Bartin, Ardahan, Igdir, Yalova and Kilis, municipal solid waste generation is less than 50,000 t per annum, therefore, these cities are omitted from the calculations. Since city wise calorific value data is not available, the calorific value range, between 2.0 and 6.0 MJ, given in Table 4, is used to calculate minimum and maximum electricity production potentials from municipal solid waste in Turkish cities via fossil fuel co-firing. It is assumed that the electric efficiency from MSW combustion is 20% [49]. The electricity production potentials from municipal solid waste co-firing and its potential supply rate of the electricity demand for 81 cities of Turkey, between 2012 and 2023 are calculated and reported in Tables 6 and 7, respectively.

Results showed that in Istanbul, Ankara and Izmir, approximately 1900, 650 and 550 GWh worth of electricity could have been produced via municipal solid waste combustion in the year 2012, which are the highest estimated generation rates in the country. It is also calculated that by the year 2023, the electricity generation potentials from MSW in these cities could rise up to 2200, 750 and 650 GWh, respectively. Nationwide in the year 2012, 8500 GWh worth of electricity could have been produced

Table 6
Estimated electricity production from municipal solid waste via combustion in mass burners, GWh. Given for 81 cities of Turkey, between 2012 and 2023. N/A: Data is not calculated for cities with annual MSW production less than 50,000 t. Assuming 20% electric efficiency and the calorific value for MSW as 2.0 to 6.0 MJ/kg.

City	Year		
	2012	2018	2023
Adana	94–282	101–303	105–315
Adıyaman	15–45	16–48	17–51
Afyonkarahisar	28–84	30–90	32–96
Ağrı	12–36	13–39	13–39
Amasya	14–42	15–45	16–48
Ankara	228–684	244–732	255–765
Antalya	102–306	109–327	114–342
Artvin	N/A–N/A	N/A–N/A	N/A–N/A
Aydın	39–117	42–126	44–132
Balıkesir	51–153	54–162	57–171
Bilecik	8–24	9–27	9–27
Bingöl	7–21	8–24	8–24
Bitlis	8–24	8–24	9–27
Bolu	10–30	11–33	12–36
Burdur	8–24	9–27	9–27
Bursa	98–294	105–315	109–327
Çanakkale	18–54	19–57	20–60
Çankırı	6–18	7–21	7–21
Çorum	18–54	19–57	20–60
Denizli	32–96	34–102	36–108
Diyarbakır	43–129	46–138	49–147
Edirne	22–66	24–72	25–75
Elazığ	23–69	24–72	25–75
Erzincan	10–30	10–30	11–33
Erzurum	21–63	23–69	24–72
Eskişehir	31–93	33–99	35–105
Gaziantep	47–141	50–150	53–159
Giresun	10–30	10–30	11–33
Gümüşhane	N/A–N/A	N/A–N/A	N/A–N/A
Hakkari	N/A–N/A	N/A–N/A	N/A–N/A
Hatay	43–129	46–138	48–144
Isparta	16–48	17–51	18–54
Mersin	64–192	69–207	72–216
İstanbul	653–1959	698–2094	732–2196
İzmir	192–576	205–615	215–645
Kars	8–24	8–24	8–24
Kastamonu	13–39	14–42	15–45
Kayseri	53–159	56–168	59–177
Kırklareli	16–48	18–54	18–54
Kırşehir	10–30	11–33	11–33
Kocaeli	59–177	63–189	66–198
Konya	74–222	80–240	83–249
Kütahya	33–99	36–108	37–111
Malatya	24–72	25–75	27–81
Manisa	55–165	59–177	61–183
Kahramanmaraş	29–87	31–93	33–99
Mardin	17–51	18–54	19–57
Muğla	45–135	48–144	51–153
Muş	N/A–N/A	N/A–N/A	N/A–N/A
Nevşehir	12–36	13–39	14–42
Niğde	13–39	14–42	15–45
Ordu	17–51	18–54	19–57
Rize	7–21	7–21	8–24
Sakarya	27–81	29–87	31–93
Samsun	35–105	38–114	39–117
Siirt	8–24	8–24	9–27
Sinop	7–21	8–24	8–24
Sivas	21–63	22–66	23–69
Tekirdağ	43–129	46–138	48–144
Tokat	23–69	24–72	25–75
Trabzon	17–51	18–54	19–57
Tunceli	N/A–N/A	N/A–N/A	N/A–N/A
Şanlıurfa	35–105	38–114	40–120
Uşak	13–39	14–42	15–45
Van	23–69	25–75	26–78
Yozgat	14–42	15–45	16–48
Zonguldak	17–51	18–54	19–57
Aksaray	13–39	14–42	14–42
Bayburt	N/A–N/A	N/A–N/A	N/A–N/A
Karaman	7–21	8–24	8–24

Table 6 (*continued*)

City	Year		
	2012	2018	2023
Kırıkkale	15–45	16–48	17–51
Batman	13–39	14–42	14–42
Şırnak	14–42	14–42	15–45
Bartın	N/A–N/A	N/A–N/A	N/A–N/A
Ardahan	N/A–N/A	N/A–N/A	N/A–N/A
Iğdır	N/A–N/A	N/A–N/A	N/A–N/A
Yalova	N/A–N/A	N/A–N/A	N/A–N/A
Karabük	8–24	8–24	8–24
Kilis	N/A–N/A	N/A–N/A	N/A–N/A
Osmaniye	12–36	13–39	14–42
Düzce	14–42	15–45	16–48
Total	2880–8640	3080–9240	3226–9678

Table 7
Potential supply rate of electricity via municipal solid waste combustion, %. Given for 81 cities of Turkey, between 2012 and 2023. N/A: Data is not calculated for cities with annual MSW production less than 50,000 t. Assuming 20% electric efficiency and the calorific value for MSW as 2.0–6.0 MJ/kg.

City	Year		
	2012	2018	2023
Adana	2–6	1.2–3.6	0.8–2.4
Adıyaman	1.4–4.2	0.9–2.7	0.6–1.8
Afyonkarahisar	2.1–6.3	1.3–3.9	0.9–2.7
Ağrı	3.2–9.6	2–6	1.4–4.2
Amasya	2.5–7.5	1.6–4.8	1.1–3.3
Ankara	2–6	1.3–3.9	0.9–2.7
Antalya	1.6–4.8	1–3	0.7–2.1
Artvin	N/A–N/A	N/A–N/A	N/A–N/A
Aydın	2–6	1.2–3.6	0.8–2.4
Balıkesir	1.7–5.1	1.1–3.3	0.7–2.1
Bilecik	0.6–1.8	0.4–1.2	0.3–0.9
Bingöl	4.4–13.2	2.8–8.4	1.9–5.7
Bitlis	3–9	1.9–5.7	1.3–3.9
Bolu	1.1–3.3	0.7–2.1	0.5–1.5
Burdur	0.9–2.7	0.6–1.8	0.4–1.2
Bursa	1–3	0.6–1.8	0.4–1.2
Çanakkale	0.4–1.2	0.3–0.9	0.2–0.6
Çankırı	2.1–6.3	1.3–3.9	0.9–2.7
Çorum	2.2–6.6	1.4–4.2	1–3
Denizli	1.1–3.3	0.7–2.1	0.5–1.5
Diyarbakır	3–9	1.9–5.7	1.3–3.9
Edirne	1.8–5.4	1.2–3.6	0.8–2.4
Elazığ	2–6	1.3–3.9	0.9–2.7
Erzincan	3–9	1.9–5.7	1.3–3.9
Erzurum	1.9–5.7	1.2–3.6	0.8–2.4
Eskişehir	1.3–3.9	0.8–2.4	0.6–1.8
Gaziantep	0.9–2.7	0.6–1.8	0.4–1.2
Giresun	1.8–5.4	1.1–3.3	0.8–2.4
Gümüşhane	N/A–N/A	N/A–N/A	N/A–N/A
Hakkari	N/A–N/A	N/A–N/A	N/A–N/A
Hatay	0.7–2.1	0.4–1.2	0.3–0.9
Isparta	1.5–4.5	1–3	0.7–2.1
Mersin	1.7–5.1	1.1–3.3	0.8–2.4
İstanbul	1.8–5.4	1.1–3.3	0.8–2.4
İzmir	1.1–3.3	0.7–2.1	0.5–1.5
Kars	2.4–7.2	1.5–4.5	1–3
Kastamonu	1.7–5.1	1.1–3.3	0.7–2.1
Kayseri	1.6–4.8	1–3	0.7–2.1
Kırklareli	0.9–2.7	0.6–1.8	0.4–1.2
Kırşehir	2.4–7.2	1.5–4.5	1.1–3.3
Kocaeli	0.5–1.5	0.3–0.9	0.2–0.6
Konya	1.3–3.9	0.8–2.4	0.6–1.8
Kütahya	2.4–7.2	1.5–4.5	1–3
Malatya	1.8–5.4	1.1–3.3	0.8–2.4
Manisa	1.6–4.8	1–3	0.7–2.1
Kahramanmaraş	0.8–2.4	0.5–1.5	0.4–1.2
Mardin	1.4–4.2	0.9–2.7	0.6–1.8
Muğla	1.9–5.7	1.2–3.6	0.8–2.4
Muş	N/A–N/A	N/A–N/A	N/A–N/A

Table 7 (*continued*)

City	Year		
	2012	2018	2023
Nevşehir	1.8–5.4	1.2–3.6	0.8–2.4
Niğde	1.4–4.2	0.9–2.7	0.6–1.8
Ordu	1.6–4.8	1–3	0.7–2.1
Rize	1–3	0.6–1.8	0.4–1.2
Sakarya	1.2–3.6	0.7–2.1	0.5–1.5
Samsun	1.5–4.5	1–3	0.7–2.1
Siirt	2.1–6.3	1.3–3.9	0.9–2.7
Sinop	2.3–6.9	1.4–4.2	1–3
Sivas	1.6–4.8	1–3	0.7–2.1
Tekirdağ	0.7–2.1	0.4–1.2	0.3–0.9
Tokat	3–9	1.9–5.7	1.3–3.9
Trabzon	1.4–4.2	0.9–2.7	0.6–1.8
Tunceli	N/A–N/A	N/A–N/A	N/A–N/A
Şanlıurfa	1.2–3.6	0.8–2.4	0.5–1.5
Uşak	1.2–3.6	0.8–2.4	0.5–1.5
Van	2.7–8.1	1.7–5.1	1.1–3.3
Yozgat	2.3–6.9	1.5–4.5	1–3
Zonguldak	0.6–1.8	0.3–0.9	0.2–0.6
Aksaray	1.9–5.7	1.2–3.6	0.8–2.4
Bayburt	N/A–N/A	N/A–N/A	N/A–N/A
Karaman	1.2–3.6	0.8–2.4	0.5–1.5
Kırıkkale	2.4–7.2	1.5–4.5	1–3
Batman	2.3–6.9	1.5–4.5	1–3
Şırnak	4.1–12.3	2.6–7.8	1.8–5.4
Bartın	N/A–N/A	N/A–N/A	N/A–N/A
Ardahan	N/A–N/A	N/A–N/A	N/A–N/A
Iğdır	N/A–N/A	N/A–N/A	N/A–N/A
Yalova	N/A–N/A	N/A–N/A	N/A–N/A
Karabük	0.8–2.4	0.5–1.5	0.4–1.2
Kilis	N/A–N/A	N/A–N/A	N/A–N/A
Osmaniye	0.8–2.4	0.5–1.5	0.4–1.2
Düzce	1.6–4.8	1–3	0.7–2.1
Total	1.4–4.2	0.9–2.7	0.6–1.8

from municipal solid waste, which could rise up to 9700 GWh by the year 2023. Currently, guaranteed tariff for electricity produced from biomass is around 10.0 eurocent/kWh in Turkey [50]. Thus, countrywide electricity worth approximately 900 million € could have been generation via municipal solid waste combustion, annually. In the three biggest cities, Istanbul, Ankara and Izmir, electricity worth 220, 70 and 60 million € could have been generated annually.

Due to large population of these three cities, these results are already expected. However, for cities with population less than 500,000 the electricity generation rates are calculated to be considerably low. On the other hand, from the supply rate perspective, up to 13% of Bingol's and Sirnak's electricity demand could be supplied via combustion of municipal solid waste for power production in 2012, which are amongst the highest in the country, followed by Diyarbakir at 9% supply rate. These cities have lower GDP than the country average, but, their electricity consumption is also low and consequently making the supply rate of MSW based electricity generation amongst the highest in the country. Meanwhile, in Istanbul, Ankara and Izmir, the estimated maximum electricity supply rates were from MSW combustion is estimated to be 6%, 6% and 3%, respectively, which are just above or equal the country average. The projections showed that, due to decline in Turkey's population growth and significant increase the gross domestic product per capita and energy consumption, the potential share of electricity generation from municipal solid waste will decrease with time. In the three major cities Istanbul, Ankara and Izmir, the maximum estimated supply rates would be between 1% and 3%, by the year 2023.

Results confirmed that MSW based electricity generation could be higher in the cities with higher GDP and population, however due to higher electricity consumption in these cities the supply

rates were significantly lower than the cities with lower GDPs. Even though the municipal solid waste generation is considerably high in Turkey, due to the lower calorific value and higher moisture content, electricity generation from municipal solid waste combustion does not provide major economic return. In addition, mass burning of municipal solid waste creates major environmental problems due to pollutant discharge and it is extremely important to optimise combustion and flue gas cleaning systems to have a low environmental impact based on the emission limits [51]. Currently, the best alternative for energy recovery from MSW is controlled methane production at landfills.

3.2. Estimated biogas and concurrent electricity production potential of municipal solid waste in 81 cities of Turkey, between 2012 and 2023

Theoretical and experimental studies indicate that complete anaerobic biodegradation of municipal solid wastes generates around 200 m^3 of methane per dry tonne of contained biomass, however, the reported rate of generation of methane in industrial anaerobic digestion reactors ranges from 40 to 80 m^3 per tonne of organic wastes [52]. Landfill gas generally contains 60%–65% methane and 35%–40% carbon dioxide. According to Themelis and Ulloa, the maximum amount of methane that can be generated during anaerobic decomposition of the organic content of municipal solid waste can be determined via Eq. 4 [52]:

$$C_6H_{10}O_4 + 1.5H_2O \rightarrow 3.25CH_4 + 2.75CO_2 \tag{4}$$

In Eq. 4, $C_6H_{10}O_4$ is the average molecular structure of the organic compounds in municipal solid waste if one excludes the minor element [53], H_2O is water, CH_4 is methane and CO_2 is carbon dioxide. Based on the data for the average moisture and organic content of municipal solid waste given in Table 4, and following the methodology of Themelis and Ulloa it is estimated that 1 t of landfilled biomass in Turkey contains 190–250 kg or 1.3–1.7 kmole of organics, $C_6H_{10}O_4$. A simple material balance, based on Eq. 4, showed that a complete reaction would generate 4.2–5.5 kmoles or 67–88 kg of methane per tonne of municipal solid waste. Therefore, at standard temperature and pressure, assuming 1 kmole of CH_4 is equivalent to 22.4 l, on average one tonne of municipal solid waste could generate 94.0–123.0 m^3 of methane in the landfills of Turkey.

In a recent study by Demir et al., methane generation rates for two test cells, one operated with and one without leachate recirculation at Odayeri Sanitary landfill in Istanbul showed that the initial biochemical methane production potentials to be 34.5 m^3 per tonne of municipal solid waste on wet basis [54]. Thus, more than 75% of the methane is emitted to the atmosphere uncontrollably, assuming theoretical generation rate to be 120 m^3 of methane per tonne of landfilled MSW. Assuming, 97% of the municipal solid waste produced in Turkish cities is landfilled properly, potential methane generation rates from the landfills in these cities, between 2012 and 2023, are calculated and reported in Table 8.

It is estimated that in the year 2012, approximately 3100 million m^3 of methane has been emitted from the landfills in Turkey. The emission rates in Istanbul, Ankara and Izmir were also at staggering: 700, 250, 200 million m^3. In the year 2023, it is estimated that nationwide emissions will reach to 3500 million m^3, and in Istanbul, Ankara, and Izmir: 800, 280 and 240 million m^3, respectively. Assuming the calorific value of methane as close to 10 kWh per m^3 [55,56], on average 94.0–123.0 m^3 of methane generation per tonne of municipal solid waste, 25% capture rate, 40% electric efficiency in combined heat and power (CHP) plants, the potential electricity generation from methane that can be harnessed at the landfills of 81 cities of Turkey,

Table 8
Estimated methane production, million m^3, from the landfills for 81 cities of Turkey, between 2012 and 2023. Assuming 94.0–123.0 m^3 of methane generation per tonne of MSW landfilled.

City	Year		
	2012	2018	2023
Adana	80–104	85–111	89–117
Adıyaman	13–17	14–18	14–19
Afyonkarahisar	24–31	25–33	27–35
Ağrı	10–13	11–14	11–15
Amasya	12–16	13–17	13–17
Ankara	193–253	206–270	216–283
Antalya	86–113	92–121	97–127
Artvin	3–4	3–4	3–4
Aydın	33–43	35–46	37–49
Balıkesir	43–56	46–60	48–63
Bilecik	7–9	8–10	8–10
Bingöl	6–8	7–9	7–9
Bitlis	7–9	7–9	7–10
Bolu	9–12	9–12	10–13
Burdur	7–9	7–10	8–10
Bursa	83–108	88–116	93–121
Çanakkale	15–19	16–21	17–22
Çankırı	5–7	6–7	6–8
Çorum	15–20	16–21	17–22
Denizli	27–35	29–38	30–40
Diyarbakır	37–48	39–51	41–54
Edirne	19–24	20–26	21–27
Elazığ	19–25	20–27	21–28
Erzincan	8–11	9–11	9–12
Erzurum	18–24	19–25	20–27
Eskişehir	26–35	28–37	30–39
Gaziantep	40–52	43–56	45–58
Giresun	8–11	9–11	9–12
Gümüşhane	3–3	3–4	3–4
Hakkari	3–3	3–4	3–4
Hatay	36–48	39–51	41–53
Isparta	13–18	14–19	15–20
Mersin	54–71	58–76	61–80
İstanbul	553–723	591–773	619–810
İzmir	163–213	174–227	182–238
Kars	6–8	7–9	7–9
Kastamonu	11–14	12–15	12–16
Kayseri	45–58	48–62	50–65
Kırklareli	14–18	15–19	16–20
Kırşehir	8–11	9–12	9–12
Kocaeli	49–65	53–69	55–73
Konya	63–82	67–88	71–92
Kütahya	28–37	30–39	32–41
Malatya	20–26	21–28	23–29
Manisa	46–61	50–65	52–68
Kahramanmaraş	25–32	26–35	28–36
Mardin	14–19	15–20	16–21
Muğla	38–50	41–54	43–56
Muş	5–6	5–7	5–7
Nevşehir	10–13	11–14	12–15
Niğde	11–15	12–16	13–17
Ordu	15–19	16–20	16–21
Rize	6–7	6–8	6–8
Sakarya	23–30	25–32	26–34
Samsun	30–39	32–42	33–44
Siirt	6–8	7–9	7–9
Sinop	6–8	7–9	7–9
Sivas	18–23	19–25	20–26
Tekirdağ	36–47	39–51	41–53
Tokat	19–25	20–27	21–28
Trabzon	14–19	15–20	16–21
Tunceli	2–3	2–3	2–3
Şanlıurfa	30–39	32–42	34–44
Uşak	11–14	12–15	12–16
Van	19–25	21–27	22–29
Yozgat	12–15	13–17	13–17
Zonguldak	14–19	15–20	16–21
Aksaray	11–14	12–15	12–16
Bayburt	2–2	2–2	2–3
Karaman	6–8	6–8	7–9
Kırıkkale	13–17	14–18	14–19

Table 8 (*continued*)

City	Year		
	2012	2018	2023
Batman	11–14	12–15	12–16
Şırnak	11–15	12–16	13–17
Bartın	5–6	5–7	5–7
Ardahan	2–2	2–2	2–2
Iğdır	4–6	5–6	5–7
Yalova	7–9	7–9	8–10
Karabük	6–8	7–9	7–9
Kilis	3–4	4–5	4–5
Osmaniye	10–13	11–14	12–15
Düzce	12–16	13–17	13–18
Total	2437–3189	2606–3410	2730–3572

Table 9
Estimated electricity generation potentials, GWh, from methane harnessing at the landfills in 81 cities of Turkey, between 2012 and 2023. Assuming 25% capture rate, 40% electric efficiency.

City	Year		
	2012	2018	2023
Adana	64–83	68–89	71–94
Adıyaman	10–14	11–14	11–15
Afyonkarahisar	19–25	20–26	22–28
Ağrı	8–10	9–11	9–12
Amasya	10–13	10–14	10–14
Ankara	154–202	165–216	173–226
Antalya	69–90	74–97	78–102
Artvin	2–3	2–3	2–3
Aydın	26–34	28–37	30–39
Balıkesir	34–45	37–48	38–50
Bilecik	6–7	6–8	6–8
Bingöl	5–6	6–7	6–7
Bitlis	6–7	6–7	6–8
Bolu	7–10	7–10	8–10
Burdur	6–7	6–8	6–8
Bursa	66–86	70–93	74–97
Çanakkale	12–15	13–17	14–18
Çankırı	4–6	5–6	5–6
Çorum	12–16	13–17	14–18
Denizli	22–28	23–30	24–32
Diyarbakır	30–38	31–41	33–43
Edirne	15–19	16–21	17–22
Elazığ	15–20	16–22	17–22
Erzincan	6–9	7–9	7–10
Erzurum	14–19	15–20	16–22
Eskişehir	21–28	22–30	24–31
Gaziantep	32–42	34–45	36–46
Giresun	6–9	7–9	7–10
Gümüşhane	2–2	2–3	2–3
Hakkari	2–2	2–3	2–3
Hatay	29–38	31–41	33–42
Isparta	10–14	11–15	12–16
Mersin	43–57	46–61	49–64
İstanbul	442–578	473–618	495–648
İzmir	130–170	139–182	146–190
Kars	5–6	6–7	6–7
Kastamonu	9–11	10–12	10–13
Kayseri	36–46	38–50	40–52
Kırklareli	11–14	12–15	13–16
Kırşehir	6–9	7–10	7–10
Kocaeli	39–52	42–55	44–58
Konya	50–66	54–70	57–74
Kütahya	22–30	24–31	26–33
Malatya	16–21	17–22	18–23
Manisa	37–49	40–52	42–54
Kahramanmaraş	20–26	21–28	22–29
Mardin	11–15	12–16	13–17
Muğla	30–40	33–43	34–45
Muş	4–5	4–6	4–6
Nevşehir	8–10	9–11	10–12

Table 9 (*continued*)

City	Year		
	2012	2018	2023
Niğde	9–12	10–13	10–14
Ordu	12–15	13–16	13–17
Rize	5–6	5–6	5–6
Sakarya	18–24	20–26	21–27
Samsun	24–31	26–34	26–35
Siirt	5–6	6–7	6–7
Sinop	5–6	6–7	6–7
Sivas	14–18	15–20	16–21
Tekirdağ	29–38	31–41	33–42
Tokat	15–20	16–22	17–22
Trabzon	11–15	12–16	13–17
Tunceli	2–2	2–2	2–2
Şanlıurfa	24–31	26–34	27–35
Uşak	9–11	10–12	10–13
Van	15–20	17–22	18–23
Yozgat	10–12	10–14	10–14
Zonguldak	11–15	12–16	13–17
Aksaray	9–11	10–12	10–13
Bayburt	2–2	2–2	2–2
Karaman	5–6	5–6	6–7
Kırıkkale	10–14	11–14	11–15
Batman	9–11	10–12	10–13
Şırnak	9–12	10–13	10–14
Bartın	4–5	4–6	4–6
Ardahan	2–2	2–2	2–2
Iğdır	3–5	4–5	4–6
Yalova	6–7	6–7	6–8
Karabük	5–6	6–7	6–7
Kilis	2–3	3–4	3–4
Osmaniye	8–10	9–11	10–12
Düzce	10–13	10–14	10–14
Total	1950–2551	2085–2728	2184–2858

between 2012 and 2023, are calculated and reported in Table 9. The potential electricity supply rate of electricity generation from methane combustion in Turkish cities, between 2012 and 2023, are also calculated and reported in Table 10.

It is estimated that in the year 2012, 2500 GWh of electricity could have been produced at the landfills of Turkey. In the year 2012, the maximum electricity generation potentials from in the three big cities: Istanbul, Ankara, and Izmir are estimated to be 560, 200, and 160 GWh, respectively. Thus, if the municipal solid waste in Turkish cities is treated properly using landfill bioreactor systems for biogas harnessing, around 1.2% of the country's annual electricity consumption could be supplied in 2012. This supply rate would decline to approximately 0.5% by the year 2023 or approximately 2900 GWh. Assuming 10 eurocent/kWh for electricity generated from methane combustion [50], nationwide electricity worth approximately 300 million € could have been generation from municipal solid waste annually. In the three biggest cities, Istanbul, Ankara and Izmir, electricity worth 65, 23 and 19 million € could have been generated annually by 2023.

3.3. *Estimated greenhouse gas emissions savings via combustion of methane emitted from municipal solid waste in 81 cities of Turkey, between 2012 and 2023*

Methane capture and combustion at the landfills does not only provide economic return but also help to tackle climate change due to greenhouse gas emission savings. Complete combustion of 1 mol of methane yields in generation of 1 mol carbon dioxide and 1 mol water vapour. Although water vapour is considered as a greenhouse gas, as a rule of thumb, its global warming potential is not calculated and used for greenhouse gas emission estimations.

Table 10
Potential supply rate of electricity via combustion of methane harnessed at landfills, %. Given for 81 cities of Turkey, between 2012 and 2023. Assuming 25% capture rate, 40% electric efficiency.

City	Year		
	2012	2018	2023
Adana	1.3–1.7	0.8–1.1	0.6–0.8
Adıyaman	0.9–1.3	0.6–0.8	0.4–0.5
Afyonkarahisar	1.4–1.9	0.9–1.2	0.6–0.8
Ağrı	2.1–2.7	1.4–1.7	0.9–1.2
Amasya	1.8–2.3	1.1–1.5	0.7–1
Ankara	1.3–1.8	0.9–1.1	0.6–0.8
Antalya	1.1–1.4	0.7–0.9	0.5–0.6
Artvin	0.6–0.8	0.3–0.5	0.2–0.3
Aydın	1.3–1.7	0.8–1.1	0.6–0.8
Balıkesir	1.2–1.5	0.7–1	0.5–0.7
Bilecik	0.4–0.5	0.3–0.3	0.2–0.2
Bingöl	3–3.6	2.1–2.5	1.4–1.6
Bitlis	2.3–2.7	1.4–1.6	0.9–1.2
Bolu	0.7–1	0.4–0.6	0.3–0.4
Burdur	0.7–0.8	0.4–0.5	0.3–0.3
Bursa	0.6–0.8	0.4–0.5	0.3–0.4
Çanakkale	0.3–0.4	0.2–0.2	0.1–0.2
Çankırı	1.3–2	1–1.2	0.6–0.8
Çorum	1.5–2	0.9–1.2	0.7–0.9
Denizli	0.7–0.9	0.5–0.6	0.3–0.4
Diyarbakır	2.1–2.6	1.3–1.7	0.9–1.1
Edirne	1.3–1.6	0.8–1	0.5–0.7
Elazığ	1.3–1.8	0.8–1.1	0.6–0.7
Erzincan	1.9–2.8	1.3–1.7	0.8–1.2
Erzurum	1.3–1.7	0.8–1.1	0.6–0.8
Eskişehir	0.9–1.2	0.6–0.8	0.4–0.5
Gaziantep	0.6–0.8	0.4–0.5	0.3–0.4
Giresun	1.1–1.7	0.8–1	0.5–0.7
Gümüşhane	1.1–1.1	0.6–1	0.4–0.6
Hakkari	1.3–1.3	0.8–1.2	0.5–0.8
Hatay	0.5–0.6	0.3–0.4	0.2–0.3
Isparta	1–1.3	0.6–0.9	0.4–0.6
Mersin	1.2–1.5	0.7–1	0.5–0.7
İstanbul	1.2–1.6	0.8–1	0.5–0.7
İzmir	0.7–1	0.5–0.6	0.3–0.4
Kars	1.6–1.9	1.1–1.3	0.7–0.8
Kastamonu	1.2–1.4	0.8–0.9	0.5–0.7
Kayseri	1.1–1.4	0.7–0.9	0.5–0.6
Kırklareli	0.6–0.7	0.4–0.5	0.3–0.3
Kırşehir	1.5–2.2	1–1.5	0.7–0.9
Kocaeli	0.3–0.4	0.2–0.3	0.1–0.2
Konya	0.9–1.2	0.6–0.7	0.4–0.5
Kütahya	1.6–2.2	1–1.3	0.7–0.9
Malatya	1.2–1.6	0.7–1	0.5–0.7
Manisa	1.1–1.4	0.7–0.9	0.5–0.6
Kahramanmaraş	0.6–0.7	0.3–0.5	0.2–0.3
Mardin	0.9–1.2	0.6–0.8	0.4–0.5
Muğla	1.2–1.7	0.8–1.1	0.5–0.7
Muş	1.1–1.4	0.7–1	0.4–0.6
Nevşehir	1.2–1.5	0.8–1	0.6–0.7
Niğde	1–1.3	0.6–0.8	0.4–0.6
Ordu	1.1–1.4	0.7–0.9	0.5–0.6
Rize	0.7–0.9	0.4–0.5	0.3–0.3
Sakarya	0.8–1	0.5–0.7	0.3–0.4
Samsun	1.1–1.4	0.7–0.9	0.4–0.6
Siirt	1.4–1.7	1–1.1	0.6–0.7
Sinop	1.6–1.9	1.1–1.3	0.7–0.8
Sivas	1–1.3	0.7–0.9	0.5–0.6
Tekirdağ	0.5–0.6	0.3–0.4	0.2–0.3
Tokat	2–2.7	1.3–1.7	0.9–1.1
Trabzon	0.9–1.2	0.6–0.8	0.4–0.5
Tunceli	2.1–2.1	1.2–1.2	0.8–0.8
Şanlıurfa	0.8–1	0.5–0.7	0.3–0.5
Uşak	0.8–1	0.5–0.7	0.4–0.5
Van	1.7–2.3	1.2–1.5	0.8–1
Yozgat	1.6–2	1–1.4	0.6–0.9
Zonguldak	0.4–0.5	0.2–0.3	0.2–0.2
Aksaray	1.4–1.7	0.9–1.1	0.6–0.8
Bayburt	2.4–2.4	1.4–1.4	0.9–0.9
Karaman	0.9–1	0.5–0.6	0.4–0.5
Kırıkkale	1.6–2.2	1–1.3	0.7–0.9
Batman	1.6–2	1.1–1.3	0.7–0.9
Şırnak	2.7–3.6	1.8–2.3	1.2–1.6
Bartın	1.2–1.5	0.7–1.1	0.5–0.7
Ardahan	2–2	1.2–1.2	0.8–0.8
Iğdır	2.3–3.9	1.8–2.3	1.2–1.8
Yalova	0.6–0.8	0.4–0.4	0.2–0.3
Karabük	0.5–0.6	0.4–0.4	0.2–0.3
Kilis	1.3–2	1.2–1.5	0.8–1
Osmaniye	0.6–0.7	0.4–0.5	0.3–0.3
Düzce	1.2–1.5	0.7–1	0.4–0.6
Total	0.9–1.2	0.6–0.8	0.4–0.5

Table 11
Greenhouse gas emission savings, million tonnes CO_2 equivalent, via combustion of methane generated at the landfills in 81 cities of Turkey. Assuming 25% capture rate, 40% electric efficiency.

City	Year		
	2012	2018	2023
Adana	0.3–0.3	0.3–0.3	0.3–0.3
Adıyaman	0–0.1	0.1–0.1	0.1–0.1
Afyonkarahisar	0.1–0.1	0.1–0.1	0.1–0.1
Ağrı	0–0	0–0.1	0–0.1
Amasya	0–0.1	0–0.1	0–0.1
Ankara	0.6–0.9	0.7–0.9	0.7–1
Antalya	0.3–0.3	0.3–0.4	0.4–0.4
Artvin	0–0	0–0	0–0
Aydın	0.1–0.2	0.1–0.2	0.1–0.2
Balıkesir	0.2–0.2	0.2–0.2	0.2–0.2
Bilecik	0–0	0–0	0–0
Bingöl	0–0	0–0	0–0
Bitlis	0–0	0–0	0–0
Bolu	0–0	0–0	0–0
Burdur	0–0	0–0	0–0
Bursa	0.3–0.3	0.3–0.3	0.4–0.4
Çanakkale	0.1–0.1	0.1–0.1	0.1–0.1
Çankırı	0–0	0–0	0–0
Çorum	0.1–0.1	0.1–0.1	0.1–0.1
Denizli	0.1–0.1	0.1–0.1	0.1–0.2
Diyarbakır	0.1–0.2	0.1–0.2	0.2–0.2
Edirne	0.1–0.1	0.1–0.1	0.1–0.1
Elazığ	0.1–0.1	0.1–0.1	0.1–0.1
Erzincan	0–0	0–0	0–0
Erzurum	0.1–0.1	0.1–0.1	0.1–0.1
Eskişehir	0.1–0.1	0.1–0.1	0.1–0.1
Gaziantep	0.2–0.2	0.2–0.2	0.2–0.2
Giresun	0–0	0–0	0–0
Gümüşhane	0–0	0–0	0–0
Hakkari	0–0	0–0	0–0
Hatay	0.1–0.2	0.1–0.2	0.2–0.2
Isparta	0–0.1	0.1–0.1	0.1–0.1
Mersin	0.2–0.3	0.2–0.3	0.2–0.3
İstanbul	1.8–2.3	1.9–2.5	2–2.7
İzmir	0.5–0.7	0.6–0.8	0.6–0.8
Kars	0–0	0–0	0–0
Kastamonu	0–0.1	0–0.1	0–0.1
Kayseri	0.2–0.2	0.2–0.2	0.2–0.2
Kırklareli	0.1–0.1	0.1–0.1	0.1–0.1
Kırşehir	0–0	0–0	0–0
Kocaeli	0.2–0.2	0.2–0.3	0.2–0.3
Konya	0.2–0.3	0.3–0.3	0.3–0.3
Kütahya	0.1–0.1	0.1–0.1	0.1–0.2
Malatya	0.1–0.1	0.1–0.1	0.1–0.1
Manisa	0.2–0.2	0.2–0.2	0.2–0.3
Kahramanmaraş	0.1–0.1	0.1–0.1	0.1–0.1
Mardin	0.1–0.1	0.1–0.1	0.1–0.1
Muğla	0.1–0.2	0.2–0.2	0.2–0.2
Muş	0–0	0–0	0–0
Nevşehir	0–0	0–0.1	0–0.1
Niğde	0–0.1	0–0.1	0–0.1

Table 11 (*continued*)

City	Year		
	2012	2018	2023
Ordu	0.1–0.1	0.1–0.1	0.1–0.1
Rize	0–0	0–0	0–0
Sakarya	0.1–0.1	0.1–0.1	0.1–0.1
Samsun	0.1–0.1	0.1–0.2	0.1–0.2
Siirt	0–0	0–0	0–0
Sinop	0–0	0–0	0–0
Sivas	0.1–0.1	0.1–0.1	0.1–0.1
Tekirdağ	0.1–0.2	0.1–0.2	0.2–0.2
Tokat	0.1–0.1	0.1–0.1	0.1–0.1
Trabzon	0.1–0.1	0.1–0.1	0.1–0.1
Tunceli	0–0	0–0	0–0
Şanlıurfa	0.1–0.1	0.1–0.2	0.1–0.2
Uşak	0–0.1	0–0.1	0–0.1
Van	0.1–0.1	0.1–0.1	0.1–0.1
Yozgat	0–0.1	0–0.1	0–0.1
Zonguldak	0.1–0.1	0.1–0.1	0.1–0.1
Aksaray	0–0.1	0–0.1	0–0.1
Bayburt	0–0	0–0	0–0
Karaman	0–0	0–0	0–0
Kırıkkale	0–0.1	0.1–0.1	0.1–0.1
Batman	0–0.1	0–0.1	0–0.1
Şırnak	0–0.1	0–0.1	0–0.1
Bartın	0–0	0–0	0–0
Ardahan	0–0	0–0	0–0
Iğdır	0–0	0–0	0–0
Yalova	0–0	0–0	0–0
Karabük	0–0	0–0	0–0
Kilis	0–0	0–0	0–0
Osmaniye	0–0	0–0.1	0–0.1
Düzce	0–0.1	0–0.1	0–0.1
Total	7.9–10.4	8.7–11.2	9.3–11.7

Methane has a global warming 23 times higher than carbon dioxide in a time horizon of 100 years [57]. This means 1 metric - tonnes of methane is equivalent to emissions of 23 metric tonnes of carbon dioxide.

Assuming the density of methane and carbon dioxide at standard temperature and pressure to be 0.668 and 1.842 kg/m^3, respectively, 25% capture rate at landfills and complete combustion based on Eq. 5, the potential greenhouse gas emission savings via methane combustion in 81 cities of Turkey, between 2012 and 2023, are calculated and reported in Table 11.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{5}$$

It is estimated that in the year 2012, potential greenhouse gas emission savings up to 10 million tonnes of CO_2 equivalent could have been achieved via methane harnessing at the landfills of Turkish cities for power generation. Based on the current technology methane capture rates are estimated to be 25% in the calculation, therefore, with the advancement in technology the greenhouse gas emission saving could also increase with time. The potential emission savings in Istanbul, Ankara and Izmir are estimated to be staggering: 2.3, 0.9, and 0.7 million tonnes of CO_2 equivalent respectively in 2012. And by the year 2023, it is estimated that nationwide emission savings could reach up to 12 million tonnes of CO_2, and in Istanbul, Ankara, and Izmir: 2.7, 1.0 and 0.8 million tonnes of CO_2 equivalent, respectively.

4. Conclusions

Municipal solid waste generation is a major problem in Turkey and it would keep on increasing in the upcoming years due to increasing population and GDP per capita. Currently, energy recovery from MSW is less than 1% countrywide and urgent action must be taken by the local authorities and central government. In this study, the potential of electricity generation via MSW combustion and methane harnessing at the landfills of 81 Turkish cities are estimated in detail. The results showed the utmost importance and benefit of energy recovery from municipal solid waste in both economic and environmental perspectives. Consequently, this study can be further used as a reference work for the analysis of biogas and municipal solid waste combustion investments in Turkey, and their environmental impacts in the following years from both academic and economic perspective.

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References

[1] Historical overview, 1927–2000 population censuses. Turkish Statistical Institute. 〈http://www.turkstat.gov.tr〉; 2012.
[2] Brice WC. The population of Turkey in 1950. The Geographical Journal 1954;120:347–52.
[3] Kearney C. Emerging markets research: trends, issues and future directions. Emerging Markets Review 2012;13:159–83.
[4] Kankal M, Akpinar A, Komurcu MI, Ozsahin TS. Modeling and forecasting of Turkey's energy consumption using socio-economic and demographic variables. Applied Energy 2011;88:1927–39.
[5] Turkey. Wikipedia the free Encyclopedia, 〈http://en.wikipedia.org/wiki/Turkey〉; 2010.
[6] The results of address based population registration system—2011. Turkish Statistical Institute. 〈http://www.turkstat.gov.tr〉; 2012.
[7] Ogulata RT. Energy sector and wind energy potential in Turkey. Renewable and Sustainable Energy Reviews 2003;7:469–84.
[8] Ergin E. Turkey's 2012 energy import bill may reach $65 bln-minister. New York, NY, USA: Thomson Reuters; 2012.
[9] Gokoluk S. In: Serkin G, editor. Lira falls 1st Day in three as US treasury beats Turkish debt. Bloomberg News: Bloomberg Businessweek; 2012.
[10] Turkish current account gap narrowed for first time in 2 years in November. Republic of Turkey: Ministry of Economy. 〈http://www.economy.gov.tr〉; 2012.
[11] Turkey posts record current account deficit. Hurriyet Daily News. 〈http://www.hurriyetdailynews.com/turkey-posts-record-current-account-deficit.aspx?pageID=238&nID=13690&NewsCatID=344〉; 2012.
[12] The municipal waste statistics—2010. Turkish Statistical Institute. http://www.turkstat.gov.tr; 2012.
[13] Yedla S, Parikh JK. Development of a purpose built landfill system for the control of methane emissions from municipal solid waste. Waste Management 2002;22:501–6.
[14] Zamorano M, Ignacio Pérez Pérez J, Aguilar Pavés I, Ramos Ridao Á. Study of the energy potential of the biogas produced by an urban waste landfill in Southern Spain. Renewable and Sustainable Energy Reviews 2007;11:909–22.
[15] Popov V. A new landfill system for cheaper landfill gas purification. Renewable Energy 2005;30:1021–9.
[16] Read AD, Hudgins M, Phillips P. Perpetual landfilling through aeration of the waste mass; lessons from test cells in Georgia (USA). Waste Management 2001;21:617–29.
[17] Murto M, Bjornsson L, Mattiasson B. Impact of food industrial waste on anaerobic co-digestion of sewage sludge and pig manure. Journal of Environmental Management 2004;70:101–7.
[18] Consonni S, Giugliano M, Grosso M. Alternative strategies for energy recovery from municipal solid waste: Part B: Emission and cost estimates. Waste Management 2005;25:137–48.
[19] Combustion. United States Environmental Protection Agency. 〈http://www.epa.gov/osw/nonhaz/municipal/combustion.htm〉; 2012.
[20] McKay G. Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: review. Chemical Engineering Journal 2002;86:343–68.
[21] Travis CC, Hattemer-Frey HA. Human exposure to dioxin from municipal solid waste incineration. Waste Management 1989;9:151–6.
[22] Turkey's energy strategy. Republic of Turkey: Ministry of Foreign Affairs. 〈http://www.mfa.gov.tr〉; 2011.
[23] The EU's target for renewable energy: 20% by 2020. House of Lords European Union Committee; 2008. p. 58.
[24] Seidl I, Tisdell CA. Carrying capacity reconsidered: from Malthus' population theory to cultural carrying capacity. Ecological Economics 1999;31:395–408.
[25] Tuckwell HC. A study of some diffusion models of population growth. Theoretical Population Biology 1974;5:345–57.
[26] Estimations and projections of population growth rate, 1986–2025. Turkish Statistical Institute, 〈http://www.turkstat.gov.tr〉; 2012.
[27] Ankara: Turkish Statistical Institute; 2012.

[28] Dyson B, Chang NB. Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modeling. Waste Management 2005;25:669–79.
[29] Vij D. Urbanization and solid waste management in India: present practices and future challenges. Procedia—Social and Behavioral Sciences 2012;37:437–47.
[30] Azapagic A, Perdan S. Sustainable development in practice: case studies for engineers and scientists. Chichester, UK: John Wiley & Sons; 2011.
[31] Municipal solid waste and its role in sustainability. A position paper prepared by IEA Bioenergy. IEA Bioenergy. 〈http://www.ieabioenergy.com/media/40_IEAPositionPaperMSW.pdf〉; 2012.
[32] Yildiz S, Yaman C, Demir G, Ozcan HK, Coban A, Okten HE, et al. Characterization of municipal solid waste in Istanbul, Turkey. Environmental Progress & Sustainable Energy 2012. http://dx.doi.org/10.1002/ep.11640.
[33] Kanat G. Municipal solid-waste management in Istanbul. Waste Management 2010;30:1737–45.
[34] Dolgen D, Sarptas H, Alpaslan N, Kucukgul O. Energy potential of municipal solid wastes. Energy Sources 2005;27:1483–92.
[35] Agdag ON. Comparison of old and new municipal solid waste management systems in Denizli, Turkey. Waste Management 2009;29:456–64.
[36] Nas SS, Bayram A. Municipal solid waste characteristics and management in Gumushane, Turkey. Waste Management 2008;28:2435–42.
[37] Sokka L, Antikainen R, Kauppi PE. Municipal solid waste production and composition in Finland—Changes in the period 1960–2002 and prospects until 2020. Resources, Conservation and Recycling 2007;50:475–88.
[38] Daskalopoulos E, Badr O, Probert SD. Municipal solid waste: a prediction methodology for the generation rate and composition in the European Union countries and the United States of America. Resources, Conservation and Recycling 1998;24:155–66.
[39] Jumbe CBL. Cointegration and causality between electricity consumption and GDP: empirical evidence from Malawi. Energy Economics 2004;26:61–8.
[40] Ediger VS, Akar S. ARIMA forecasting of primary energy demand by fuel in Turkey. Energy Policy 2007;35:1701–8.
[41] Erdogdu E. Electricity demand analysis using cointegration and ARIMA modelling: A case study of Turkey. Energy Policy 2007;35:1129–46.
[42] Ediger VS, TatlIdil H. Forecasting the primary energy demand in Turkey and analysis of cyclic patterns. Energy Conversion and Management 2002;43:473–87.
[43] Melikoglu M. Vision 2023: feasibility analysis of Turkey's renewable energy projection. Renewable Energy 2013;50:570–5.
[44] Electricity Distribution and Consumption Statistics—2010. Turkish electricity distribution company (TEDAS). 〈http://www.tedas.gov.tr〉; 2012.
[45] Ozturk HK, Ceylan H, Canyurt OE, Hepbasli A. Electricity estimation using genetic algorithm approach: a case study of Turkey. Energy 2005;30:1003–12.
[46] Vision 2023 technology insight project. Energy and natural resources panel report. Ankara: Tubitak; 2003. p. 56.
[47] World Bank technical guidance report—municipal solid waste incineration. Washington: The International Bank for Reconstruction and Development/The World Bank. 〈www.worldbank.org〉; 1999. p. 111.
[48] Ruth LA. Energy from municipal solid waste: a comparison with coal combustion technology. Progress in Energy and Combustion Science 1998;24:545–64.
[49] Murphy JD, McKeogh E. Technical, economic and environmental analysis of energy production from municipal solid waste. Renewable Energy 2004;29:1043–57.
[50] Sekercioglu S, Yilmaz M. Renewable energy perspectives in the frame of Turkey's and the EU's energy policies. Energy Conversion and Management 2012;63:233–8.
[51] Liang Z, Ma X. Mathematical modeling of MSW combustion and SNCR in a full-scale municipal incinerator and effects of grate speed and oxygenenriched atmospheres on operating conditions. Waste Management 2010;30:2520–9.
[52] Themelis NJ, Ulloa PA. Methane generation in landfills. Renewable Energy 2007;32:1243–57.
[53] Themelis NJ, Kim YH. Material and energy balances in a large-scale aerobic bioconversion cell. Waste Management & Research 2002;20:234–42.
[54] Demir A, Bilgili MS, Ozkaya B. Effect of leachate recirculation on refuse decomposition rates at landfill site: a case study. International Journal of Environment and Pollution 2004;21:175–87.
[55] Cuzin N, Farinet JL, Segretain C, Labat M. Methanogenic fermentation of cassava peel using a pilot plug flow digester. Bioresource Technology 1992;41:259–64.
[56] Fisher ST. Electrical induction heating: a new approach to underground coal gasification. Energy Conversion 1979;19:77–84.
[57] Chu H, Hosen Y, Yagi KNO. N_2O, CH_4 and CO_2 fluxes in winter barley field of Japanese Andisol as affected by N fertilizer management. Soil Biology and Biochemistry 2007;39:330–9.